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Long-Time Study of Cement Performance in Concrete

Chapter 11

Report on the Condition of Three Test Pavements after 15 years of Service

BY

FRANK H. JACKSON

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Chapter 11—Report on the Condition of Three Test Pavements After 15 Years of Service

By FRANK H. JACKSON†

SYNOPSIS

This report discusses the present condition of three test pavements built about 15 years ago. One pavement is in western New York in a region subject to severe natural weathering, one in central Missouri where exposure conditions are moderately severe, and one in western South Carolina where mild weather prevails. Twenty-seven cements, differing widely in their chemical and physical properties, were used in these pavements.

After 15 years service the New York pavement exhibits surface scaling in varying amounts on almost all sections containing the non-air-entraining cements. However, except for the Type IV and Type V cements, there is no indication that any one non-air-entraining cement or type of non-air-entraining cement is more resistant to scaling than another. Type IV and Type V cements show greater average resistance to scaling than the other non-air-entraining types. All sections containing air-entraining cements are still completely free from surface scale.

Aside from some light scale or surface wear on the South Carolina project and some D-cracking on the Missouri road, neither of which can be associated in any way with a particular cement or cement type, all of the cements have performed equally well on both projects. Under the conditions prevailing on these projects, variations in the chemical composition and fineness of the cement, within the limits represented by this study, appear to be without significance insofar as resistance to freezing and thawing is concerned.

INTRODUCTION

About 15 years ago, the Portland Cement Association, in cooperation with a number of federal, state, and private agencies, initiated an extensive field program to study cement performance in concrete. This investigation was the outgrowth of a suggestion made by P. H. Bates, then chief of the division of clay and silicate products at the National Bureau of Standards and also chairman of the American Society for Testing Materials Committee C-1 on cement. It was at about this time that ASTM adopted the five-type specification for portland cement, thus breaking away from the "single standard" philosophy which had dominated the committee's thinking for many years.

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†Member American Concrete Institute, Consulting Engineer, Chevy Chase, Md.

During the decade just preceding this ASTM action, there were many discussions regarding the desirability of setting up requirements to cover portland cement to meet specific needs, such as early strength, low heat of hardening, and sulfate resistance. Also, many user organizations, not satisfied with ASTM's single standard, were issuing their own specifications. These included the highway departments of New York and certain other states whose specifications included special requirements covering compound composition; the specifications for "low-heat" and "moderate-heat" cements of the U. S. Bureau of Reclamation and the Federal Specification Board; the "Type B" cement specifications of the Tennessee Valley Authority; and, finally, the elaborate specifications covering manufacturing controls issued by the New York Board of Water Supply under guidance of the late Thaddeus Merriman.

One of the most controversial questions involved in these discussions concerned the need for a so-called Type II cement and, if such a need existed, whether it should be considered as an improved "general purpose" cement or merely defined as a moderate-heat cement. Those in favor of the first position cited numerous laboratory data, including extensive tests by the U. S. Bureau of Reclamation which showed that resistance to frost action was improved by limiting the quantity of potential tricalcium aluminate (C_3A) in the cement. Those in favor of the second position pointed to the excellent service records of many concrete structures containing cements high in C_3A. The final decision of the ASTM was to delete reference to improved durability in the specifications for Type II cement and to consider it strictly as a cement with moderate heat of hydration and moderate sulfate resistance.

Another problem giving much concern 15 years ago was surface deterioration. Pavements in many of the northern states where chemicals were being used for ice removal were beginning to scale badly and, in some cases, to develop D-lines* (cracks) along joints and cracks which, it was feared, might be the prelude to early disintegration. Highway engineers were greatly concerned and they scrutinized cement as one possible source of trouble. At that time the great improvement in the durability of concrete made possible by the use of air entrainment was just beginning to be realized, and many engineers were not convinced—incidentally some of them are still not convinced—that the answer to the durability problem lay in the proper application of this principle rather than in restrictions in the chemical composition of the cement.

The foregoing constitute some of the reasons that prompted Mr. Bates to suggest to Frank Sheets, then president of the Portland Cement Association, that the industry sponsor a program to study the performance of cement in job-size concrete structures of various types and so located as to be exposed to a wide variety of climatic conditions. The idea met with ready

*In a concrete pavement, deterioration due to weathering is usually evidenced first by the appearance of fine, more or less closely spaced parallel surface cracks along the joints and structural cracks and sometimes along the free edges of the pavement slab. These cracks are frequently filled with a dark colored deposit—principally calcium carbonate—whence the name "D-cracks" or "deposit-cracks."

acceptance, and the Portland Cement Association appropriated $350,000 to carry out the work. An advisory committee was appointed, consisting of eight members representing consumer groups and four members representing the cement industry, with Mr. Bates as chairman. Several changes in the personnel of this committee have since taken place, and the committee is now under the chairmanship of R. F. Blanks. This committee has had complete responsibility for the conduct of the investigation from the start. It developed the original program and has reviewed and approved all progress reports thus far published.

Long-Time Study cements

Twenty-seven different portland cements, varying in physical and chemical properties through the entire range permitted under the then current specifications of the American Society of Testing Materials (C 150) were used in these tests. Twenty-one of these cements were of the normal, non-air-entraining type then in general use and were classified as follows: eight were Type I; five, Type II; three, Type III; four, Type IV; and one, Type V. In addition, six air-entraining cements were made by intergrinding flake Vinsol resin with the clinkers used in making the corresponding non-air-entraining cements. Four of these were Type I; one, Type II; and one, Type III. In the tables and discussion which follow, the various cements are identified by number, the first digit in each case indicating the type and the second digit the number of the cement within the type. The six air-entraining cements are identified by the letter "T" immediately following the cement identification number.

Test program

With some exceptions, at least 24 of the 27 cements were used in each of a number of full-size and near full-size concrete structures located in various parts of the country. These included three concrete pavements, totaling approximately 6 miles of standard two-lane construction, one located in southwestern New York in an area subject to severe natural weathering, one in central Missouri where the exposure is moderately severe, and one in western South Carolina where mild weather conditions prevail. There are also four installations of reinforced concrete piles, three in salt water, and one in fresh. The test cements were also used in the parapet wall of an earth-filled dam; in the walkway slabs of a multiple arch dam; in test specimens subject to action of alkali soils; and in two installations of near job-size specimens—one near Chicago, where exposure conditions are severe and the other near Macon, Ga., under mild exposure conditions.

To minimize, insofar as practical, the effect of accidental variables, each cement was used a number of times in each structure. For example, on the New York test road, each cement was used in four test sections each 12 ft wide and 150 ft long. The cements were used in rotation, the sequence being such as to avoid abrupt changes in finishing characteristics. Not all of the cements were used in all of the structures. However, the entire 27 were used

approximately 80 times, with 22 cements being used 95 times. This, together with the fact that approximately 50,000 bbl of cement were required for the entire project, will give some idea of the magnitude of the operation.

During the 15 years that have elapsed since these structures were built, a number of reports showing the progress of deterioration due to weathering have been issued. Most of these are readily available in the *Proceedings* of the American Concrete Institute. Several have also been issued as bulletins by the Portland Cement Association. A list of published reports covering the project is given in the bibliography.

THE TEST ROADS

Three reports covering the test roads have already been published. The first of these appeared as a portion of a paper entitled "Why Type II Cement?" prepared by the writer in 1949.[8] This was followed by a more detailed report on the New York test road after 7½ years of service.[9] Finally, there appeared in 1953 the 10-year report on the Long-Time Study.[10] In these reports the discussion, insofar as pavement performance was concerned, was confined entirely to the New York road. The only reference to the Missouri and South Carolina roads was to point out that at the end of 10 years exposure no differences in behavior attributable to cements had developed on either of these projects.

In the present report it is proposed to discuss the condition of all three test roads as revealed by inspections made by the writer and others* during the summer of 1957. After 15 years exposure in actual service it should be possible to draw some rather definite conclusions regarding the comparative weathering characteristics of these cements. However, other factors in addition to the cement affect pavement durability. These include: (1) the physical properties and grading of the aggregates used in the concrete; (2) the proportions, including cement, water, and air content; (3) the consistency; and (4) the methods of construction, particularly methods of placing and finishing. Any comparisons of cement performance on the different roads must necessarily give consideration to these other factors.

AGGREGATES

Local aggregates were used on each project. These differed considerably in mineral composition as well as in grading, thus further complicating the comparisons of cement performance.

A natural sand meeting state specifications 47L and two sizes of crushed gravel were used in New York. The fine aggregate was a moderately coarse sand containing about equal parts of quartz and feldspar and with about 60 percent passing the No. 14 sieve and about 15 percent passing the No. 48

*The following engineers participated in the 1957 inspections:
Missouri: D. G. Gothan, Missouri Highway Department; H. Allen and G. V. Joines, Bureau of Public Roads.
South Carolina: Messrs. Herriot, Armstrong, and Beckham, South Carolina Highway Department; H. Allen and K. F. Shippey, Bureau of Public Roads; F. R. McMillan, consulting engineer; and C. C. Oleson, Portland Cement Association.
New York: W. H. Ketchum, New York Department of Public Works; Messrs. H. Allen, Groves, and Mabel, Bureau of Public Roads; and I. L. Tyler, Portland Cement Association.

sieve. Sodium sulfate loss averaged 7 percent at five cycles and 9 percent at ten cycles. The coarse aggregate was a crushed gravel of glacial origin composed of argillaceous sandstone with an appreciable amount of shale. The maximum size was 2 in. Sodium sulfate tests, run on separated sizes, averaged about 10 percent loss at five cycles and 27 percent loss at ten cycles.

On the South Carolina project two sizes of fine and one size of coarse aggregate were used. A mixture of the two sands in the proportions used in the work showed 93 percent passing the No. 16 sieve and 17 percent passing the No. 50 sieve. The combined fine aggregate was considerably finer than the sands used on either of the other projects. The coarse aggregate was a crushed granite ranging from 2 in. maximum size to No. 4. Sodium sulfate tests were run on separated sizes of the coarse aggregate with weight loss varying from a maximum of 13 percent at five cycles for the 1½-2-in. size to less than 1 percent for the ¾-1½-in. size.

Fine aggregate used on the Missouri project was a natural sand from Boonville, Mo., averaging about 75 percent passing the No. 16 sieve and about 10 percent passing the No. 50 sieve. The coarse aggregates were two sizes of rather soft, high-absorption, crushed cherty limestone, the combined grading running from 1½ in. maximum to No. 4. The coarse aggregate contained an appreciable amount of dust of fracture. Absorption averaged 2.6 percent.

COMPOSITION OF THE CONCRETE

Standard paving mixtures conforming to the requirements of the states involved were used for the non-air-entrained concrete on all of the projects. For the air-entrained concrete, the usual practice of reducing the sand content by an amount necessary to maintain approximately the same cement content as in the non-air-entrained mixes was followed. In New York, actual cement content, as determined from field measurements, varied from a minimum of 6.0 sacks per cu yd to a maximum of 6.7 sacks per cu yd, with an average of about 6.5 sacks per cu yd.* In Missouri, the cement content ranged from 5.4 to 5.9 sacks per cu yd, with an average of 5.8. The range in South Carolina was from 5.5 to 6.0, with an average of 5.9. However, differences in cement content between individual cements on any one project did not, as a rule, exceed ± 0.2 sack. Differences of this order are believed to be without significant effect on comparisons of cement performance.

Except for one group of sections where the amount of mixing water was increased to give a slump of about 5 in., the New York road program called for a 3-in. slump. Actually, due to poor water control, slump test results varied considerably, not only from section to section but also within each section. A slightly drier mix averaging 2½-in. slump with better water control was used in Missouri and South Carolina. Air contents of the non-air-entrained concrete, as calculated from the field measurements, generally averaged 1.0 percent or less. An exception to this was Cement 41. Air con-

*Variations in cement content on the New York project are discussed in considerable detail in Reference 9.

tent of concrete containing this cement averaged 2.1 percent in New York, 2.0 percent in Missouri, and 1.0 percent in South Carolina. This variation was probably due to the intermittent use of rosin as a grinding aid in the manufacture of this cement.

Air contents of the air-entrained concrete varied from 2.5 to 6.2 percent in New York, from 2.7 to 3.7 percent in Missouri, and from 3.4 to 3.6 percent in South Carolina. With the exception of concrete containing Cement 16T, the air contents of all of the air-entrained concretes were low in terms of present-day practice; the average of all values was about 3 percent.

METHODS OF CONSTRUCTION

Construction practices followed those of the states involved. Types and efficiency of the power equipment used for placing and finishing varied considerably as between jobs. An old, underpowered, double-screed finisher was used in New York. In general, this equipment was not powerful enough to properly compact concrete of less than 4-in. slump. Furthermore, the operation of the equipment was inconsistent, the number of passes varying from one to as many as seven in some cases. This variability of operation imposed an added burden on the longitudinal float that followed. In addition, the comparatively large number of low, honeycombed, or torn areas left by the transverse screeds necessitated much more than the normal amount of "carry-back," thus further increasing the burden on the finishing machines. The final finish was obtained by means of a 12 in. wide plywood belt followed by a burlap drag, and, finally, brooming with 20-in. stiff-fiber brooms. The record indicates that the amount of surface manipulation that followed the operation of power equipment was less than on the average construction operation. Cotton mats, placed as soon as the surface was hard enough to withstand damage, kept wet 3 days, and then removed, were used for curing.

In South Carolina the only power equipment used to handle the concrete, after it had been deposited on the subgrade, was an old-type two-screed finisher which served also as a spreader. Number of passes varied from two to seven, with an average of about three. On this job a "Flexplane" machine was used to install a longitudinal premolded joint after which the surface was floated with hand-operated longitudinal float. The operation of this float varied widely, depending upon the degree of hardening which had taken place before the float was brought into operation. Sometimes it was used simply as a float, at other times as a combination tamper and float. Final finishing was by longitudinal steel straightedges followed by belting with a 10-in. canvas belt and dragging with an 18-in. burlap drag. Curing was by the use of wet burlap for 10 hr followed by waterproof paper for 3 days.

Concrete on the Missouri road was distributed on the subgrade with a power-screw spreader and finished with a two-screed finishing machine with tamper operating between the screeds. Both screeds and the tamper operated during the first pass, the screeds only during the second pass. A power-

operated longitudinal float followed, usually operating close to the finisher. This in turn was followed by straightedging with 10-ft steel straightedges and an 8-in. canvas belt. The final texture was obtained by brooming. Curing was by means of wet cotton mats applied for 3 days.

CLIMATIC CONDITIONS

As previously noted, the three locations were chosen to provide natural weathering conditions varying from the quite severe climate of southwestern New York, through the moderately severe climate of central Missouri, to the comparatively mild climate of western South Carolina. The principal difference in the conditions that prevail in New York as compared to Missouri and South Carolina lies in the average annual snowfall which is as high as 95 in. in the vicinity of the New York road, compared to an average of 20 in. in Missouri and less than 1 in. in South Carolina. Total precipitation, on the other hand, averages about 50 in. per year in South Carolina as compared to 40 in. per year in Missouri and New York. Temperatures during the winter months are not greatly different in New York and Missouri, averaging only about 4 deg lower at the former location. From 1941 to 1956, the average number of days per month during which the temperature fell below 32 F for the five winter months, November through March, was 21 in Missouri as compared to 24 in New York, not a great difference. In South Carolina the average temperatures were about 10 F higher.

Due to ice conditions and to the heavy snowfall, ice control chemicals have been used quite extensively on the New York road, compared to a sparing use in Missouri and no use at all in South Carolina. It is believed that these chemicals (mostly sodium and calcium chloride) have probably contributed more to the surface scaling which has developed on certain non-air-entraining cement sections of the New York road than any other single factor. The fact that practically no scaling has developed on the Missouri road, where ice control chemicals were used only sparingly, confirms this observation. However, none of the air-entrained concrete sections on the New York Test Road have scaled, even under the heavy and repeated applications of chemically treated abrasives to which they have been subjected. This will be discussed more fully in a following section.

TRAFFIC CONDITIONS

The average total daily traffic on the three test roads, based on 1957 surveys conducted by the Bureau of Public Roads, together with the number of vehicles having gross loads of over 9 tons and the approximate percentages of gross loads over 9 tons are given in Table 1.

The average total daily traffic on the South Carolina road was over five times as great as reported for Missouri and almost four times as great as indicated for New York. However, the percentage of gross loads over 9 tons was about the same in all cases.

TABLE 1—1957 TRAFFIC ON THE TEST ROADS

Project	Total average vehicles per day of 24 hr	Gross loads over 9 tons	Approximate percent of gross loads over 9 tons
Missouri	1848	80	4.3
South Carolina	10258	301	3.0
New York	2743	90	3.3

PRESENT CONDITION OF THE TEST ROADS

New York

The New York test road constitutes Project 1 of the Long-Time Study. It is 2.6 miles long, located in southwestern New York on State Route 17, between Wellsville and Bolivar. It was constructed during late summer and fall of 1942 and has therefore gone through 15 winters. The test road is divided into three parts, designated as Project 1, 1A and 1B. Project 1 contains 24 of the test cements (all 21 of the non-air-entraining and three of the air-entraining cements) and was designed to compare them on the basis of their resistance to frost action uncomplicated by the action of chloride salts. Unfortunately, it was found necessary as early as 1945 to apply ice control chemicals to certain portions of Project 1, including the sections lying on a slight grade immediately west of the village of Allentown, as well as to certain sections east of the town. It is rather difficult to make comparisons based on the effect of natural weathering alone since precise locations in which the ice control chemicals were employed cannot be clearly defined.

Project 1A was set up to study the effect of using a somewhat wetter mix (5-in. slump) as compared to the 3-in. slump used in Project 1. Three of the non-air-entraining cements used in Project 1 together with their air-entraining counterparts (a total of six cements) were used in this project.

Project 1B contains six of the non-air-entraining cements together with their air-entraining counterparts, 12 cements in all. These sections were constructed on a fairly steep grade at the east end of the test road where it was anticipated that ice control chemicals would be used regularly.

The New York test road has been inspected approximately annually since its construction. The writer has participated in a number of these inspections, including the most recent made in June, 1957. A complete record of the behavior of the test sections including structural cracking, which has been extensive, has been obtained. However, in accordance with the primary objectives of the Long-Time Study, principal emphasis has been directed toward obtaining evidence indicative of lack of durability or weather resistance. Careful notes were taken during the earlier inspections regarding the condition of the joints, including the formation of D-cracks,* spalling, raveling, and scaling. The formation of D-cracks along construction joints and structural cracks was formerly considered quite significant as indicating a ten-

*See definition in footnote, p. 1018.

dency toward premature weathering or lack of durability of the concrete slab as a whole. However, continued observation of this and many other concrete roads has indicated that progressive deterioration following D-cracking is usually confined to the vicinity of the joint itself and does not, as a rule, progress to the interior of the slab. On the New York test road, the D-cracking noted in the earlier reports has probably progressed by now to a condition where raveling or scaling along the joint has occurred. This is the usual result of D-cracking. However, the practice of overfilling the joints with asphalt during routine maintenance operations usually leaves an excess of asphalt in the surface which has prevented any detailed examination of the concrete in this case. For this reason no attempt to rate the joints, as in previous inspections, was made in 1957. Attention of the observers was confined to recording to the nearest 5 percent the appreciable amount of surface scale that has developed on most of the non-air-entrained sections.

Table 2 shows in round figures the amount of surface scale (expressed as a percentage of the total area of the slab) that has occurred on Project 1 as of: March, 1945; August, 1951; June, 1955; and June, 1957. Although, as previously stated, no sections on this portion of the test road were supposed to have been salted, the record shows that beginning in 1945 several areas, including the grade west of Allentown, have had intermittent applications of chemically treated abrasives. Since it is impossible to identify with certainty the exact boundaries of the salt treated sections and also because the salt treated abrasives may have been tracked some distance along the road from the point of application, it is difficult to separate the salted from the unsalted portions of the pavement. However, if we assume that salts were used on the grade west of Allentown and also in the vicinity of certain intersecting roads, it is possible to spot some of the locations which were probably salted. Test sections corresponding to these locations are shown by an asterisk in Table 2. Reference to the table shows at once that most of the sections in Rounds 2 and 4 were subject to salt action and that, as a rule, the percentage of scale on these sections is considerably higher than on the sections placed during Rounds 1 and 3.

There are, however, two exceptions to this general rule. In the case of the three air-entraining cements (12T, 16T, and 21T) we find no evidence of scaling in any of the rounds in spite of the fact that sections containing these cements in Rounds 2 and 4 were subject to salting in the same manner as the non-air-entraining cements. This confirms a fact now well recognized—that air-entrained concrete is highly resistant to surface scaling resulting from alternate freezing and thawing, either with or without the accompanying action of chemically treated abrasives. The other exception is that the non-air-entraining Type IV and V cements show considerably less scale than the other non-air-entraining types. Omitting Section 51-2, average surface scale for Type IV and V cements is about 2 percent, compared to about 30 percent for the average of Type I, II, and III cements. However, note that Cement 41 is in reality a mildly air-entraining cement (2 percent air) and that

fact may explain its excellent behavior. In the case of the other three Type IV cements, and the single Type V cement, there is no evidence in the record to indicate that entrained air exceeded 1 percent in any case.

Another point of interest in Table 2 is that, in general, the Type II cements as a group show no greater resistance to scaling than the Type I cements. This statement is made with full realization of the uncertainties involved in mak-

TABLE 2—PROGRESS OF SCALING, PROJECT 1, NEW YORK TEST ROAD

Section No.	Surface scale, percent of total area of slab				Section No.	Surface scale, percent of total area of slab			
	1945	1951	1955	1957		1945	1951	1955	1957
11 -1	0	T	5	5	22 -1	0	0	T	5
2*	5	25	55	90	2	0	T	5	15
3*	0	T	20	20	3	0	0	1	5
4*	0	T	15	15	4*	0	T	10	60
12 -1	0	T	10	5	23- 1	0	1	30	50
2*	0	5	20	20	2*	0	1	25	50
3	0	T	5	10	3	0	1	35	C
4*	0	0	1	T	4*	0	T	15	30
12T-1*	0	0	0	0	24 -1	0	1	10	35
2*	0	0	0	0	2	0	1	3	5
3	0	0	0	0	3	0	2	3	10
4	0	0	0	0	4*	T	T	20	25
13 -1	0	T	10	45	25- 1	0	T	1	10
2*	15	45	90	C	2	0	T	5	20
3	0	T	5	10	3	0	0	5	T
4*	0	T	20	50	4*	0	T	1	15
5	0	—	90	90					
14 -1	0	0	0	0	31- 1	0	T	30	60
2	0	T	5	5	2*	T	1	30	55
3	0	1	5	10	3	0	0	T	5
4*	0	1	5	10	4*	0	0	T	5
15 -1	0	T	5	5	33- 1	0	0	1	5
2*	1	15	50	90	2*	0	T	5	15
3	0	T	10	15	3	0	T	5	15
4*	0	T	40	C	4	0	0	0	T
16 -1	0	1	10	15	34 -1	0	T	20	30
2*	0	2	15	30	2*	0	15	70	C
3	0	5	25	30	3	0	T	30	35
4*	0	T	10	20	4*	0	T	25	40
5*	0	—	10	20					
16T-1	0	0	0	0	41- 1	0	0	0	0
2*	0	0	0	0	2*	0	0	0	T
3	0	0	0	0	3	0	0	0	0
4*	0	0	0	0	4	0	T	0	0
17 -1	0	T	10	20	42 -1	0	0	0	T
2*	0	5	60	C	2	0	T	1	T
3	0	T	15	20	3	0	8	0	0
4	0	T	T	5	4*	0	T	T	10
18 -1	0	T	1	T	43 -1	0	0	0	T
2*	0	5	25	50	2*	0	0	T	5
3	0	0	T	T	3	0	0	0	0
4*	0	T	10	55	4*	0	T	5	5
21- 1	0	T	1	35	43A-1	0	T	T	T
2*	0	T	10	15	2*	0	0	2	10
3	0	0	5	T	3	0	0	0	0
4*	0	0	5	35	4	0	T	0	T
21T-1	0	0	0	0	51 -1	0	0	0	T
2	0	0	0	0	2*	0	0	0	80†
3	0	0	0	0	3	0	T	1	5
4	0	0	0	0	4*	0	0	T	T

NOTE: T—trace
C—covered with bituminous materials
*Abrasives containing chemicals were probably used on this section.
†Appearance of section would indicate the condition is the result of light surface wear rather than salt scaling.

TABLE 3—PROGRESS OF SCALING, PROJECT 1A, NEW YORK TEST ROAD

Section No.	Surface scale, percent of total area of slab				Section No.	Surface scale, percent of total area of slab			
	1945	1951	1955	1957		1945	1951	1955	1957
A12 -1	0	1	20	70	A16T-1*	0	0	0	0
2*	0	1	10	30	2	0	0	0	0
3	0	2	25	35	3	0	0	0	0
4*	0	T	20	20	4*	0	0	0	0
A12T-1	0	0	0	0	A21 -1	T	1	70	C
2*	0	0	0	0	2*	0	T	50	C
3	0	0	0	0	3	0	2	50	90
4*	0	0	0	0	4*	0	1	70	C
A16 -1	0	1	20	60	A21T-1	0	0	0	0
2*	0	1	25	70	2*	0	0	0	0
3	0	10	60	80	3	0	0	0	0
4*	0	1	35	55	4*	0	0	0	0

NOTE: T—trace
C—covered with bituminous materials
*Abrasives containing chemicals were probably used on this section.

ing comparisons of the data shown. However, there is no evidence to indicate that the Type II cements were subjected either to more frequent or to heavier applications of salt treated abrasives (particularly in Round 1) than the Type I cements. Consequently, it is believed that the comparison can be considered reasonably valid.

In general, the same comments may be made with regard to the sections comprising Project 1A (5-in. slump concrete) as were made in the case of Project 1. Three of the non-air-entraining cements and their air-entraining counterparts were used in this project. The percentages of scale that had developed in Project 1A at the same four periods as shown in Table 2, are given in Table 3. It will be observed that the 12 sections containing the non-air-entraining cements have scaled badly in all four rounds whereas the corresponding 12 sections containing the air-entraining counterparts of these same cements are completely free from scale. The amount of scaling in the non-air-entraining cements in all cases is considerably higher than is shown for those same cements in Project 1 (see Table 2). This is probably due to the higher slump (and consequently higher water content) of the concrete in Project 1A. However, the outstanding fact again is the excellent performance of the air-entraining cements, none of which have shown any signs of scaling up to this time even in concrete of relatively high water content.

As previously noted, Project 1B was constructed on a considerable grade at the east end of the test road. The purpose here was to provide a comparison between the cements under conditions involving the use of chemically treated abrasives for ice control. Six of the non-air-entraining cements and the six corresponding air-entraining cements (12 cements in all) were used on this portion of the test road. All have been subjected to repeated and heavy applications of abrasives containing ice-control chemicals. The amount of scaling that has developed is shown in Table 4. Here again the principal point to be noted is the complete absence of scaling in all of the sections containing the six air-entraining cements as compared to serious scaling on

TABLE 4—PROGRESS OF SCALING, PROJECT 1B, NEW YORK TEST ROAD

Section No.	Surface scale, percent of total area of slab				Section No.	Surface scale, percent of total area of slab			
	1945	1951	1955	1957		1945	1951	1955	1957
B11 -1	10	45	85	85	B18 -1	5	25	45	60
2	1	15	30	45	2	5	1	10	20
3	T	5	10	20	3	T	10	20	30
4	T	5	10	30	4	T	5	10	10
B11T-1	0	0	0	0	B18T-1	0	0	0	0
2	0	0	0	0	2	0	0	0	0
3	0	0	0	0	3	0	0	0	0
4	0	0	0	0	4	0	0	0	0
B12 -1	15	30	75	80	B21 -1	5	30	80	C
2	2	20	50	70	2	1	5	80	C
3	T	T	5	10	3	0	5	45	C
4	T	50	C	C	4	T	30	C	C
B12T-1	0	0	0	0	B21T-1	0	0	0	0
2	0	0	0	0	2	0	0	0	0
3	0	0	0	0	3	0	0	0	0
4	0	0	0	0	4	0	0	0	0
B16 -1	15	50	90	85	B33 -1	5	45	80	C
2	5	15	40	60	2	T	20	65	60
3	T	25	40	60	3	0	0	2	5
4	T	15	40	60	4	T	1	5	10
B16T-1	0	0	0	0	B33T-1	0	0	0	0
2	0	0	0	0	2	0	0	0	0
3	0	0	0	0	3	0	0	0	0
4	0	0	0	0	4	0	0	0	0

NOTE: Chemically treated abrasives have been applied to all of the Sections of Project 1B.
T—trace
C—covered with bituminous materials

almost all of the sections containing the corresponding six non-air-entraining cements. The contrast is so great as to completely overshadow the relatively minor differences in scaling resistance indicated by the various non-air-entraining cements. This project furnishes further proof of the outstanding performance of air-entrained concrete under conditions where chemically treated sand or cinders are used extensively for ice control.

South Carolina test road

This road is Project No. 2 of the Long-Time Study. It is located in the western part of the state just southeast of Greenville. All 21 of the non-air-entraining cements and the air-entraining counterparts of three of these cements were used four times in sections 22 ft wide and 90 ft long. This made 96 test sections, each divided by contraction joints into three subsections 30 ft long, thus providing two interior joints in each test section. The entire test pavement, approximately 1.6 miles long, was constructed during the late fall of 1941, and is now 16 years old. Traffic and weather conditions which prevail on this road have already been described.

Due to the comparatively mild climate of western South Carolina, this test pavement has not been subjected to anything like the severe weather conditions that prevail in western New York where many alternations of freezing and thawing and an average annual snowfall of 90 in. may be expected. Snowfall in South Carolina is rare and the winter temperatures average several degrees higher. For these reasons certain types of defects

observed in New York, such as surface scaling and D-cracking along joints, are almost entirely absent in South Carolina. However, structural failures—that is, longitudinal and transverse cracking, corner breaks, etc.—due to traffic loads are quite frequent. Such failures are not related in any way to the weathering characteristics of the cements.

Branch and pattern cracking in some of the sections has been noted from time to time. These are the fine cracks which are often observed on flat concrete surfaces. They are most noticeable when the concrete is moist. This type of cracking does not appear to be associated with any particular cement or cement type. It is minor in extent, except in the case of Cement No. 24. In this case, Rounds 1 and 2 have been reported as affected to a marked degree whereas Rounds 3 and 4 are entirely clear. Also, there appears to have been a slight increase with time in the amount and degree of pattern cracking on Sections 24-1 and 24-2 but the concrete otherwise is still in good condition, no special maintenance measures having yet been required.

According to the 1957 inspection, tracking of bituminous material from recently placed bituminous shoulders onto the pavement has, in some cases, completely obscured the indications of surface crazing that had been noted in the earlier reports. In other cases, the concrete surface, especially the outer 3 ft, presented a somewhat mottled appearance consisting of many high and low spots. Tracking by vehicles has discolored the high spots, leaving the low spots clear, thereby accentuating the appearance of roughness. There is a distinct question in this case whether these were actually scaled areas or whether the roughened appearance was caused by wear or abrasion. Location of the test road in a mild climate with few cycles of freezing and thawing would indicate that the roughened areas probably result from wear. These areas were noted at various places along the road and did not appear to be associated with either individual cements or cement types, except that the Type III cements appeared to be free from this type of defect.

In general, the South Carolina test road is still in excellent condition. The minor defects noted in no way affect the serviceability of the road; it should give good service for many years.

Missouri test road

This is Project 3 of the Long-Time Study. The test road is located in the east-central section of the state, on Route 22 about 3 miles west of Mexico, Mo. All 21 of the non-air-entraining cements and the air-entraining counterparts of three of these cements were used in this test. Each cement was used five times in full-width sections, 22 x 75 ft, with a transverse plane of weakness in the center of each test section. This made a total test length of 9000 ft or 1.8 miles. The road, built during the summer of 1941, is now 16 years old. Traffic and weather conditions prevailing have already been described.

Several inspections of the Missouri test road have been made. The first

TABLE 5—MISSOURI TEST ROAD D-CRACKING AS OBSERVED IN 1957

Cement	Round					Cement	Round				
	1	2	3	4	5		1	2	3	4	5
11	O	O	X	X	X	31	O	O	O	O	O
12	X	O	X	O	X	33	O	O	O	O	O
12T	O	O	O	O	O	34	O	O	O	O	O
13	O	X	O	O	O						
14	O	O	X	X	NR	41	O	O	O	O	O
15	X	O	NR	O	O	42	O	O	O	X	X
16	O	O	O	O	O	43	O	O	O	O	O
16T	O	O	O	O	O	43A	O	O	O	O	X
17	O	O	O	X	NR						
18	O	O	O	O	O	51	O	O	O	O	O
21	X	O	X	X	X						
21T	O	O	O	O	O						
22	O	O	X	O	O						
23	X	O	O	X	X						
24	O	O	O	O	O						
25	O	O	X	O	X						

NOTE: O—No D-cracking or scale observed in 1957
X—D-cracking and/or scale observed in 1957
NR—No record

complete inspection was in 1942, 1 year after the road was built, the most recent in June, 1957. The pavement is still in excellent condition after 16 years service. Early inspections revealed numerous chert "pops" in the surface of the pavement. These pops do not appear to affect the structural strength or general durability of the concrete. Chert pops are almost completely absent on all sections containing the Type III cements. Otherwise they are fairly well distributed among the cements, regardless of type.

Aside from chert pops, observable defects in the Missouri test road were confined to a small amount of spalling along the joints. Some faint D-cracking was also observed at the joints; its distribution by cements and rounds is shown in Table 5. The three air-entraining cements as well as all three of the Type III and the one Type V non-air-entraining cements were completely free from D-cracking at the time of this inspection. This is also true of Type IV cements, 41 and 43. On the other hand, only three of the Type I and Type II non-air-entraining cements are completely free from D-cracking in all rounds. These are Cements 16, 18, and 24.

Defects thus far observed on the Missouri test road are not serious enough to affect the serviceability of the pavement, which is in excellent condition after 16 years use. There are practically no structural defects and the chert pops, although numerous and unsightly, have had no other adverse effects. Joint spalling is not serious enough to warrant concern, provided the joints are given proper maintenance.

SUMMARY

Project 1, the New York test road

The progress report[9] issued in 1951 states that "all six of the air-entraining cements are definitely superior to the non-air-entraining cements in resistance to surface scaling." This statement still held true in 1957. In fact, the

contrast is even more striking now due to the progressive scaling that has occurred on most of the non-air-entrained sections as compared to no scaling at all on any of the sections containing the air-entraining cements.

Except for the Types IV and V cements, there is still no evidence to indicate that any one non-air-entraining cement or any one type of non-air-entraining cement is consistently more resistant to scaling than another. In general, there is a greater difference in the amount of scale from round to round for a given cement than there is between the averages for the various cements. The Type II cements show up no better in this regard than Type I cements, a fact that may surprise many of those who have held quite firm opinions to the contrary. On the other hand, the data do show that the Type IV and V cements are much more scale resistant than the other non-air-entraining types. However, it would seem unwise to draw any general conclusion regarding the superior scale resistance of the Type IV and Type V cements based on the evidence of the New York test road alone.

The generally inconsistent behavior of many of the non-air-entraining cements as regards frost resistance suggests the probability that physical characteristics of the concrete are more important in determining its ultimate durability than is the chemical composition of the cement. This view is supported by other research studies which indicate that the physical structure of the cement paste, particularly the number of air voids per unit of volume of the paste, is a controlling factor in the matter of durability. The results of these studies should throw considerable light on the problem of reconciling certain anomalies with which we are confronted in our study of cement performance on these projects. In the meantime, we should not overlook the fact that the influence of such factors as chemical composition and fineness is, in reality, of minor significance as compared to the great improvement which results from the use of air-entrained concrete under conditions where chemicals will be used for ice removal. This is the really important lesson taught by the New York test road.

Projects 2 and 3, the South Carolina and Missouri test roads

The South Carolina and Missouri test roads are both in excellent condition after 16 years service. Such surface defects as have developed are minor and, so far, have necessitated no special maintenance measures. Sections containing both the air-entraining and the non-air-entraining cements are equally good. There has been some pattern cracking and some intermittent light scale or surface wear on the South Carolina road and a considerable number of chert pops on the Missouri road. There is some spalling as well as some D-cracking on this road also. However, none of these defects can be associated in any way with a particular cement or a particular type of cement, with the following exceptions. On the South Carolina road one of the Type II cements, No. 24, developed more than the average amount of pattern cracking in two of the four rounds containing this cement. Also, all of the sections containing the Type III cements were entirely free from the light

scale or wear observed on the South Carolina road as well as entirely free from the chert pops and D-cracking observed in Missouri.

The good record of the Type III cements in South Carolina and Missouri and the correspondingly good record of the Type IV and Type V cements in New York again emphasizes the difficulty of drawing any general conclusions regarding the superior durability of any one type of cement as compared to another. Aside from the exceptions noted, all of the cements have performed equally well on both projects. On the basis of this performance, it would certainly seem safe to assume that, under similar conditions of exposure, variations in the chemical composition and fineness of cements within the limits represented by this study, are without practical significance, insofar as frost resistance is concerned.

BIBLIOGRAPHY

1. McMillan, F. R., "Comprehensive Program of Cement Research," *Civil Engineering*, Oct. 1943.

2. McMillan, F. R., and Tyler, I. L., "Long-Time Study of Cement Performance in Concrete. Chapter 1—History and Scope," ACI JOURNAL, Feb. 1948, *Proc.* V 44, pp. 441-456. Reprinted in *PCA Bulletin* No. 26.

3. McMillan, F. R., and Hansen, W. C., "Long-Time Study of Cement Performance in Concrete. Chapter 2—Manufacture of the Test Cements," ACI JOURNAL, Mar. 1948, *Proc.* V. 44. pp. 553-604. Reprinted in *PCA Bulletin* No. 26.

4. Lerch, William, and Ford, C. L., "Long-Time Study of Cement Performance in Concrete. Chapter 3—Chemical and Physical Tests of the Cements," ACI JOURNAL, Apr. 1948, *Proc.* V. 44, pp. 745-796. Reprinted in *PCA Bulletin* No. 26.

5. Brown, L. S., "Long-Time Study of Cement Performance in Concrete. Chapter 4—Microscopic Study of the Clinkers," ACI JOURNAL, May 1948, *Proc.* V. 44, pp. 877-924. Reprinted in *PCA Bulletin* No. 26.

6. McMillan, F. R., Stanton, T. E., Tyler, I. L., and Hansen, W. C., "Long-Time Study of Cement Performance in Concrete. Chapter 5—Concrete Exposed to Sulfate Soils," *Special Publication*, American Concrete Institute, 1949, 64 pp. Reprinted as *PCA Bulletin* No. 30.

7. Verbeck, George J., and Foster, Cecil W., "Long-Time Study of Cement Performance in Concrete. Chapter 6—The Heats of Hydration of the Cements," *Proceedings*, ASTM, V. 50, 1950, pp. 1235-1262. Reprinted as *PCA Bulletin* No. 32.

8. Jackson, F. H., "Why Type II Cement?," *Proceedings*, ASTM V. 50, 1950, pp. 1210-1224.

9. Jackson, F. H., and Tyler, I. L., "Long-Time Study of Cement Performance in Concrete. Chapter 7—New York Test Road," ACI JOURNAL, June 1951, *Proc.* V. 47, pp. 773-796. Reprinted as *PCA Bulletin* No. 38.

10. Advisory Committee, Long-Time Study of Cement Performance in Concrete, "Ten-Year Report on the Long-Time Study of Cement Performance in Concrete," ACI JOURNAL, Mar. 1955, *Proc.* V. 49, pp. 601-616. Reprinted as *PCA Bulletin* No. 43.

11. Jackson, F. H., "Long-Time Study of Cement Performance in Concrete. Chapter 9—Correlation of the Results of Laboratory Tests with Field Performance Under Natural Freezing and Thawing Conditions," ACI JOURNAL, Oct. 1955, *Proc.* V. 52, pp. 159-194. Reprinted as *PCA Bulletin* No. 65.

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